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COSMOLOGY SOLVED? QUITE POSSIBLY!

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ABSTRACT

The discovery of the cosmic microwave background (CMB) in 1964 by Penzias and Wilson led to the establishment of the hot big-bang cosmological model some ten years later. Discoveries made in 1998 may ultimately have as profound an effect on our understanding of the origin and evolution of the Universe. Taken at face value, they confirm the basic tenets of Inflation + Cold Dark Matter, a bold and expansive theory that addresses all the fundamental questions left unanswered by the hot big-bang model and holds that the Universe is flat, slowly moving elementary particles provide the cosmic infrastructure, and quantum fluctuations seeded all the structure seen in the Universe today. Just as it took a decade to establish the hot big-bang model after the discovery of the CMB, it will likely take another ten years to establish the latest addition to the standard cosmology and make the answer to "Cosmology Solved?", "YES!" Whether or not 1998 proves to be a cosmic milestone, the coming avalanche of high-quality cosmological data promises to make the next twenty years an extremely exciting period for cosmology.

DEDICATION

This article is dedicated to the memory of a great scientist, my cosmological mentor, and my very dear friend, David N. Schramm. David had been scheduled to face Jim Peebles in this Great Debate; after his tragic death in a plane crash last December, I agreed to take his place in this event which is now dedicated to his memory. Throughout his career David was "bullish" on cosmology and for a number of years he had been speaking about the coming Golden Age in cosmology, where a flood of cosmological data would test the bold ideas that blossomed from the connection between the Inner Space of elementary particles and the Outer Space of cosmology which he helped to pioneer. I am certain that he would have enjoyed his role in this celebration of cosmology, and my hunch is that he would have answered the question, "Cosmology Solved?", with the answer that I have.

1 When is Cosmology Solved?

Cosmology is the scientific study of the origin and evolution of the Universe, and the word itself derives from the Greek, cosmos, meaning order. From my perspective as a particle cosmologist, I would say that Cosmology is Solved when we explain and understand the basic features of the Universe, those which define its fundamental character, in terms of a theory rooted in fundamental physics.

Solving cosmology does not mean the end of the study of the Universe, nor even the beginning of a less exciting period of astrophysical inquiry. An analogy may be helpful; we have known the laws of quantum mechanics for more than sixty years, and quantum physics continues to be a vibrant field of study, as evidenced by recent advances including the first Bose – Einstein condensates of atoms, high-temperature superconductivity, fractional quantum Hall effect, quantum computing, and quantum interference devices.

The Universe is the most amazing and wondrous "zoo" one can imagine, full of all kinds of interesting objects and a diversity of phenomena. Astrophysics is the scientific pursuit of an understanding of these objects and phenomena in terms of the laws of physics. It is difficult to imagine astrophysics ever being solved. A list of today's puzzles is challenging enough to occupy astrophysicists for decades: What are the objects that make gamma-ray bursts and how do they work?; How do galaxies form stars and light up the sky?; How are stars born?; When were the first stars born?; What mechanism makes stars explode as supernovae?; Most of the ordinary matter is not in the form of stars, but is dark – what is it?; How do planets form?; Is there life elsewhere in the Cosmos?; How do massive black holes form? What is the origin of the highest energy cosmic rays? and on and on. As we are flooded with data from new ground-based and space-based observatories and experiments in the coming years and some of these questions are answered, the list will grow longer, with new, more interesting questions being added. Cosmology solved or not, I am confident that there will be plenty of challenges for next century's astrophysicists.

The revolution in cosmology triggered by the discovery of the CMB in 1964 led to the establishment of the hot big-bang cosmological model as the standard cosmological model (see e.g., Silk, 1980; or Peebles et al 1991). I believe the hot big-bang theory will be viewed as one of the great intellectual triumphs of the 20th century. Based upon a simple mathematical model, the Friedmann – Lemaitre – Robertson – Walker (FLRW) solution of Einstein's equations, it describes accurately the evolution of the Universe from a fraction of a second after the bang until today. As discussed by Silk, the FLRW model stands upon three experimental pillars: the observed expansion of the Universe; the existence of the cosmic microwave background (CMB) radiation; and the abundance pattern of the light elements D, ^{3}He, ^{4}He, and ^{7}Li produced seconds after the bang in a sequence of nuclear reactions known as big-bang nucleosynthesis (BBN).

As successful as the FLRW cosmology is, there are a number of fundamental questions that it leaves unexplained. Here is the list of questions that I believe must be addressed before we can say "Cosmology Is Solved":

- Origin of the expansion and definitive measure of the present expansion rate H_0 (Hubble's constant).
- Origin of the heat in the Universe and a precise measure of the present temperature of the CMB.
- Full accounting of matter and energy in the Universe. From such an accounting one can infer the present rate of deceleration (or acceleration) of the expansion and the geometry of the Universe.
- Understanding of the origin of the density inhomogeneities that seeded all the structure seen in the Universe today.
- Understanding of the origin of ordinary matter and particle dark matter.
- Understanding of the dynamite behind the big bang. The term "big-bang theory" is a misnomer – it is not a theory of the big-bang event, but rather, of the events thereafter.
- Understanding of the regularity of the Universe, as evidenced by the uniformity of the CMB (temperature variations across the sky of less than one part and in 10^4 and the statistically homogeneous distribution of galaxies).
- Description of the history of the Universe from the big-bang event on.

As I will discuss in detail in Section 3, Inflation + Cold Dark Matter is a theory that addresses all of these questions as well as extending our understanding of the Universe back to times as early as 10^{-32} sec. Its fundamental predictions are that the Universe is spatially flat, that the bulk of the matter exists in the form of slowly moving elementary particles (and not the stuff that we are made of), and that diversity of structure we see in the Universe today, from galaxies to the great walls of galaxies (Geller and Huchra, 1989), arose from quantum mechanical fluctuations on subatomic scales.

2 1998 – A Most Memorable Year for Cosmology

1998 saw the first plausible, complete accounting of matter and energy in the Universe; a precision determination of the density of ordinary matter; and other strong evidence supporting the basic tenets of Inflation + Cold Dark Matter (CDM). If subsequent data and observations confirm and strengthen the case, I believe we will ultimately refer to 1998 as a turning point in cosmology as important as 1964.

As discussed by Silk, the small variations in the CMB temperature across the sky have the potential to determine the geometry of the Universe and thereby Ω_0, the fraction of critical density contributed by all forms of matter and energy. [Note, the curvature radius of the Universe and Ω_0 are related by, $R^2_{\rm curv} = H_0^{-2}/|\Omega_0 - 1|$, so that $\Omega_0 = 1$ corresponds to a flat geometry, $\Omega_0 < 1$ corresponds to negatively curved (open) geometry, and $\Omega_0 > 1$ corresponds to positively curved (closed) geometry.] In a flat Universe the differences in temperature between points on the sky are greatest when the two points are separated by about one degree; in an open Universe, they are greatest when the separation is smaller than one degree. The data that now exist indicate that the differences are indeed greatest on the one-degree scale (see Fig. 1). More measurements are being made – from balloons, in Antarctica, and on the Atacama Plateau in Chile – with definitive measurements to come from two new satellites: NASA's MAP (launch 2000) and ESA's Planck Surveyor (launch (2007). If the trend in the results continues, then we have determined that the Universe is spatially flat and $\Omega_0 = 1$.

These same measurements of the temperature variations of the CMB temperature across the sky also provide important information about the matter inhomogeneities that seeded all the structure we see in the Universe today. Recall, that as Silk explained, the pattern of hot and cold spots on the microwave sky arises due to the lumpy distribution of matter, and in this way the CMB is a snapshot of the Universe at 300,000 years after the beginning (CMB photons come directly to us from their last scattering at this time). The first mapping of the distribution of matter in early Universe using the CMB was done by NASA's COBE satellite (Smoot et al, 1992); since then, many other experiments, with better angular resolution, have "enhanced the picture." At present, the pattern of hot and cold spots indicate, though do not yet prove, that the primeval lumpiness had the following characteristics: Gaussian fluctuations in the curvature of the Universe with an approximately scale-invariant spectrum (see Fig. 1). This is precisely what inflation predicts.

Of the four light elements made in the big bang, the yield of deuterium is most sensitive to the density of ordinary matter (baryons), and for that reason David Schramm and I nicknamed it "the baryometer" (Schramm & Turner, 1998). Deuterium is also "very fragile," easily destroyed by nuclear reactions in stars. The abundance of deuterium in our local neighborhood has been known for more than twenty years, but because about half of the material around us has been through stars, we cannot interpret the locally measured abundance as the primordial, big-bang abundance. This year, David Tytler and Scott Burles (Burles & Tytler, 1998a,b) measured the deuterium abundance in very distant hydrogen clouds. Because these clouds are so distant, we are seeing them at an early time, before stars have destroyed their deuterium. Their measurement of the primeval deuterium abundance pegs the contribution of ordinary matter to be 5% of the critical density (for a Hubble constant of $65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), with a precision of better than $\pm 0.5\%$ (see Fig. 2).

In addition to pinning down the amount of ordinary matter, the Tytler – Burles measurement has allowed us to determine the total amount of matter, using a very clever technique pioneered by Simon White and his colleagues (White et al, 1993). They argue that clusters of galaxies, by virtue of their large size (tens of millions of light years in size and thousands of galaxies in number), represent a fair sample of matter in the Universe. Thus, the ratio of baryons to matter in clusters, together with the big-bang determination of the average density of baryons in the Universe serve to pin down the average matter density in the Universe:

$$\Omega_{\mathrm{Matter}} = \frac{\Omega_{\mathrm{Baryons}}}{\text{ratio of baryons to matter in clusters}} = \frac{5\%}{13\%} = 40\% \pm 10\% \qquad (1)$$

Most of the baryons in clusters exist in the form of hot, x-ray emitting gas and the intensity of x-ray emission allows a determination of the amount of ordinary matter. The total cluster mass can be determined in a number of ways: by direct mapping of the mass by gravitational lensing, by measuring the x-ray temperature, and by measuring the random motion of galaxies; all three give the same answer. The ratio of baryons to matter has been determined to be $13\% \pm 1.5\%$. This implies that matter contributes $40\% \pm 10\%$ of the critical density. (Other determinations of the matter density indicate a similar value.)

The determination that matter contributes 40% of the critical density has two implications. First, as Silk discussed, most of the matter in the Universe is not the stuff we are made out of, which follows from the inequality, $\Omega_{\mathrm{Matter}} > \Omega_{\mathrm{Baryon}}$. That is, the matter that provides the cosmic infrastructure and holds the Universe together is something exotic (or, perhaps we should say that we are made of something more exotic). That is a remarkable fact. As I will discuss, the most promising idea is that this exotic matter is relic elementary particles left over from the earliest moments of creation.

The second, equally profound implication follows from the inequality, $\Omega_0 > \Omega_{\mathrm{Matter}}$. This implies the existence of a form of matter or energy that does not clump (as evidenced by the fact that it is not found in clusters) and yet contributes 60% of the critical density. The fact that this funny component to the energy density does not clump and contributes so much of the critical density implies that it must be very elastic (the technical term is negative pressure) and leads to a striking prediction: that the expansion of the Universe should be speeding up, rather than slowing down!

This requires further explanation: According to Einstein's theory of general relativity, the source of gravity is energy density + three times the pressure (Note: matter and energy are equivalent, related by $E = mc^2$; Newton's theory of gravity holds that the source of gravity is matter alone.) If the pressure is sufficiently negative – and it must be if the additional component is to remain smooth – its gravity is repulsive! Because there is so much of this "funny" energy, the net effect of gravity on the expansion of the Universe is repulsive and so the Universe should be speeding up, rather than slowing down! Sandage's famous deceleration parameter embodies all of this, $q_0 = \frac{\Omega_0}{2}[1+3p/\rho]$ is negative if $p < -\rho/3$.

(An aside: the fact that energy density + three times pressure is the source of gravity in Einstein's theory also leads to the prediction of black holes. An object with very strong gravity needs great pressure to balance gravity; objects with stronger and stronger gravity – i.e., stars of greater and greater mass – need more and more pressure; eventually, the pressure becomes counterproductive, producing more gravity, resulting in a black hole.)

The prediction of accelerated expansion was confirmed in 1998 and completed the accounting of matter and energy in the Universe. By studying the relationship between the distances and velocities of distant galaxies by using exploding stars (supernovae of type Ia, or SNeIa) within them as standard candles, two teams (the Supernova Cosmology Project led by Saul Perlmutter and the High-redshift Search Team led by Brian Schmidt) found evidence that the Universe is speeding up, rather than slowing down (Perlmutter et al, 1998; Riess et al, 1998). Let me explain their results by telling you what they expected to find and what they actually did find. Because the expansion of the Universe is simply a scaling up of all distances, if we could measure galaxy velocities and positions today, they would obey exactly Hubble's law: recessional velocity proportional to distance ($v = H_0 d$). However, as we look far out into space, we look back in time (light travels at a finite speed), and so we are viewing distant galaxies at earlier and earlier times. If the Universe is slowing down, distant galaxies should be moving faster than Hubble's law predicts. These two groups found the opposite: distant galaxies are moving more slowly than Hubble's law predicts. The expansion is speeding up.

The simplest interpretation of their results is that vacuum energy, with pressure equal to minus its energy density, contributes about 60% of the critical density, making consistent the determinations $\Omega_0 = 1$ and $\Omega_{\rm Matter} = 0.4$. Vacuum energy is the modern term we use for Einstein's cosmological constant. It corresponds to the energy associated with the very lively quantum vacuum – pairs of particles borrowing enough energy to exist for a fleeting instant and then disappearing again.

To summarize the accounting of matter and energy in the Universe (in units of the critical density): neutrinos, 0.3% or greater; bright stars, 0.5%; total amount of ordinary matter (baryons), 5%; relic elementary particles, 35%; and vacuum energy (or something similar), 60%; for a total of 100% of the critical density (see Fig. 3). While this accounting is not definitive yet, measurements that are being made and will be made in the next years could firm it up.

(Only about one-tenth of the baryons are "visible" in the form of bright stars. Further, because there are almost as many neutrinos left over from the big bang as there are CMB photons and because evidence now exists that at least two of the neutrino species have mass, albeit very tiny (Fukuda et al, 1998), we can infer that neutrinos contribute as much mass, and perhaps even more, than stars do. However, both neutrinos and bright stars are small contributors to the total mass in the Universe.)

3 Inflation + Cold Dark Matter

In addition to providing an account of events from a fraction of a second (the time of big-bang nucleosynthesis) to the present, the hot big-bang cosmology, supplemented by the standard model of particle physics and other advances in our understanding of the fundamental particles and their interactions, provides a firm foundation for speculations about much earlier times, back to 10^{-43} sec after the beginning (earlier, the quantum nature of gravity and possibly space-time itself must be considered).

These speculations involve a crucial connection between the inner space of elementary particles and the outer space of cosmology. That connection is simple: when the Universe was young, it was a hot soup of the fundamental particles of nature, quarks, antiquarks, electrons, positrons, neutrinos, antineutrinos, photons, gluons, and other particles. To understand the earliest moments of creation, one has to understand the fundamental particles and how they interact with one another. The highly successful, standard model of particle physics provides the information needed to take us back to about 10^{-11} sec; ideas about how the forces and particles are unified (e.g., supersymmetry, grand unification and superstring theory) are needed to discuss the Universe at even earlier times.

The duality of inner space / outer space connection is also worth noting: The quark soup of the early Universe can be recreated at particle accelerators by colliding high-energy particles together; the early Universe, with its sea of extremely energetic particles that are constantly colliding, can be used to study the forces and particles at energies beyond the reach of terrestrial accelerators (see e.g., Kolb & Turner, 1990). Motivated by interesting and sometimes compelling speculations about fundamental physics and the unification of the forces of nature, the past fifteen years have seen much discussion of the earliest history of the Universe. These cosmological speculations have allowed cosmologists to address the most fundamental questions they face; conversely, cosmology has given particle physicists access to a new laboratory with virtually unlimited energy.

The most compelling idea to arise from the synthesis of elementary particle physics with cosmology is Inflation + Cold Dark Matter (Guth, 1982; Blumenthal et al, 1984). It is an expansive paradigm, deeply rooted in fundamental physics, and it has the potential to extend our understanding of the Universe back to 10^{-32} sec and to address most of the fundamental questions poised by the hot big-bang model. Inflation + Cold Dark Matter holds that most of the dark matter consists of slowly moving elementary particles; that the Universe is flat; and that the density perturbations that seeded all the structure seen today arose from quantum mechanical fluctuations on scales of 10^{-23} cm or smaller. It took a while for cosmological observers and experimentalists to take this paradigm seriously enough to try to disprove it; now, in the 1990s, it is being tested in a serious way – and is passing the tests with flying colors. (David Schramm played a very crucial role in this regard – he urged the more conservative observers to take these new ideas seriously, and with equal fervor, he urged particle cosmologists to make testable predictions.) My thesis for this debate is that the first evidence supporting the fundamental tenets of Inflation + Cold Dark Matter have been presented this year.

The key feature of inflation – and the one responsible for its name – is the tremendous burst of expansion: In 10^{-32} sec the Universe grew in size by a factor greater than it has since! I will not discuss the details of what caused this burst of expansion; it suffices to say that it is related to vacuum energy. This tremendous growth in the size of the Universe means that all we can see today originated from an extraordinarily tiny bit of the whole Universe. A tiny bit of any space appears smooth and flat – take the earth for example – and this leads to the first key prediction of inflation: the Universe should appear flat and thus the total energy density should equal the critical density. Further, it explains the large-scale regularity seen today. (The subsequent expansion of the Universe does not change the curvature or regularity; to be very precise, inflation does not predict an exactly flat Universe, and only predicts that a region much, much larger than the observable Universe is smooth.)

The quantum world of subatomic particles is in constant turmoil, fluctuating and changing. Because we do not live in the subatomic world, we are unaware of these quantum fluctuations. However, the extraordinary burst of expansion stretches quantum fluctuations to astrophysical scales, making them relevant for the Universe. And, in a well defined way, this quantum turmoil leads to the primeval lumpiness in the distribution of matter in the Universe. The quantum-born, inflation-produced fluctuations are of a form known as Gaussian scale-invariant curvature fluctuations (Guth & Pi, 1982; Hawking, 1983; Starobinskii, 1982; Bardeen, Steinhardt, and Turner, 1983). Inflation-produced, quantum fluctuations in space time itself lead to a relic background of gravitational waves that are an additional "smoking gun" signature of inflation.

On to the cold dark matter part. Inflation predicts a flat Universe; that is, total energy density equal to the critical energy density. Inflation does not predict what form or forms the critical density takes; we must rely upon astrophysical clues and measurements. Since ordinary matter (baryons) only contributes about 5% of the critical density, and there is good evidence that the total amount of matter is 40% of the critical density, there must be another form of matter in addition to baryons. The leading possibility is elementary particles left over from the earliest, fiery moments. Because of the high temperatures that existed early on, the full zoo of elementary particles was represented. Of interest for cosmology, are particles that are long lived or stable, and interact sufficiently weakly so that they would not have annihilated by the present. Generically, they fall into two classes – fast moving, or hot dark matter; and slowly moving, or cold dark matter. Neutrinos are the prime example of hot dark matter – they move quickly because they are very light. Axions and neutralinos are examples of cold dark matter. Neutralinos move slowly because they are very heavy (fifty to five hundred times the mass of a proton) Axions are extremely light (one millionth of a millionth the mass of an electron), but were produced in a very, very cold state (Bose – Einstein condensate). Both the axion and neutralino are as of yet hypothetical particles: they are predicted by theories that unify the forces and particles of Nature, but they are not yet ruled in or ruled out by experiment.

Motivated by since-refuted experimental evidence that neutrinos have enough mass to account for the critical density, hot dark matter was carefully studied in the 1980s and found wanting (White, Frenk, and Davis, 1983). With hot dark matter structure in the Universe forms from the top down: large things, like superclusters form first, and then fragment into smaller objects such as galaxies. This is because fast moving neutrinos erase lumpiness on small scales by moving from regions of greater density into regions of lower density. Observations now very clearly indicate that galaxies formed at redshifts $z \sim 2-4$, clusters formed at redshifts $z \sim 0-1$, and superclusters are just forming today. So neutrinos are out, at least as the major component of the dark matter. This leaves cold dark matter. (While apparently not a major ingredient in the cosmic mix, neutrinos may play the role of a needed cosmic spice; as discussed earlier, there is now experimental evidence that at least two of the neutrino species are massive.)

Cold dark matter particles cannot move far enough to smooth out lumpiness on small scales, and so structure forms from the bottom up: galaxies, followed by clusters of galaxies, and so on. The bulk of galaxies should form around redshifts of $2-4$, followed by clusters at redshifts $0-1$ and superclusters today. This is just what the observations of the young Universe made by the Keck 10-meter telescopes and the Hubble Space Telescope indicate.

The cold dark matter model with a cosmological constant, referred to as ΛCDM by the experts, is consistent with an enormous body of cosmological and astrophysical data, from the determinations of the age of the Universe to the pattern of hot and cold spots in the CMB (see Figs. 4, 5, and Turner, 1997; Krauss & Turner, 1995; Ostriker & Steinhardt, 1995). And now, its dramatic prediction, that the Universe should be speeding up rather than slowing down, has been verified (Riess et al, 1998; Perlmutter et al, 1998). In ΛCDM the dark energy exists in the form of spatially constant vacuum energy (Einstein's cosmological constant). It accounts for 60% of the critical energy density, but plays no direct role in the formation of cosmic structure because it cannot clump.

4 Cosmology Solved: The Case for Inflation + Cold Dark Matter

To make my case that twenty years from now cosmologists will refer to 1998 as the year Cosmology was Solved, let me return to my list of necessary elements from the first Section. Here are the explanations according to Inflation + Cold Dark Matter.

- Origin of the expansion and definitive measure of the present expansion rate H_0 (Hubble's constant). *The Universe is still expanding from the inflationary explosion. Thanks to the Hubble Space Telescope's calibration of standard cosmological candles (especially*

Type Ia supernovae), and techniques based on gravitational lensing and the influence of hot gas in clusters upon the cosmic microwave background radiation, we are zeroing in on the elusive Hubble constant: all current data are consistent with $65 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ *(Madore et al, 1998).*

- Origin of the heat in the Universe and a precise measure of the present temperature of the CMB. *The vacuum energy that drove inflation ultimately decays into radiation (heat), and according to inflation, the CMB is the primary fossil of inflation! Thanks to the extraordinary work of John Mather's COBE FIRAS team, the temperature of the CMB has been measured to 4 significant figures, as accurately as the thermometers on the COBE satellite would permit,* $T_0 = 2.728 \pm 0.002\,K$ *(Fixsen et al, 1996).*

- Full accounting of matter and energy in the Universe. *Inflation predicts that we live in a flat Universe and that the total energy density is equal to the critical density. Observations now provide the following accounting: ordinary matter, 5%; relic elementary particles, 35%; vacuum energy, 60%, for a total summing to 100% of the critical density (see Fig. 3.*

- Understanding of the origin of the density inhomogeneities that seeded all the structure seen in the Universe today. *They arose from quantum fluctuations on subatomic scales that were stretched to astrophysical size during inflation. The pattern of hot and cold spots on the CMB sky are consistent with this prediction (see Figs. 1 and 5.*

- Understanding of the origin of ordinary matter and particle dark matter. *The origin of ordinary matter in the Universe traces to a slight excess – part in* 10^{10} *of matter over antimatter in the early Universe. As the Universe cooled, all the antimatter annihilated with matter, leaving a tiny bit of matter. Because of the tremendous heat release at the end of inflation, this tiny excess of matter over antimatter must arise after inflation, by interactions among the sea of elementary particles present. A framework for understanding this – called baryogenesis – exists and only the details need to be worked out. The cold dark matter particles remain from the early moments of creation because they are stable and they are ineffective in annihilating with one another.*

- Understanding of the dynamite behind the big bang. *The explosive expansion caused by vacuum energy (or something similar) is the dynamite behind the big bang. Further, in the context of inflationary cosmology, what we previously called "The Big Bang," which was supposed to be the creation of the entire Universe, is demoted to "our big bang" and the creation of the large, smooth region of the Universe in which we live. According to Andrei Linde, if inflation occurred one, it occurred an infinite number of times and our bang is but one of an infinite number (Linde, 1990).*

- Understanding of the regularity of the Universe. *The portion of the Universe that we see is very regular because it all originated from an extraordinarily tiny portion of the Universe.*

- Description of the history of the Universe from the big-bang event on. *The events after the vacuum energy of inflation is released as heat are as in the standard hot big-bang model.*

5 Checklist for the Next Decade

As I have been careful to stress (far too carefully for a real debate), the basic tenets of Inflation + Cold Dark Matter have not yet been confirmed definitively. However, a flood of high-quality cosmological data is coming, and could make the case soon. Regardless, the flood of information will make cosmology exciting for the next decade and beyond. Here is my version of how "quite possibly" becomes "yes."

- Map of the Universe at 300,000 yrs. COBE mapped the CMB with an angular resolution of around 10°; two new satellite missions, NASA's MAP (launch 2000) and ESA's Planck Surveyor (launch 2007), will map the CMB with 100 times better resolution (0.1°). From these maps of the Universe as it existed at a simpler time, long before the first stars and galaxies, will come a gold mine of information: Among other things, a definitive measurement of Ω_0; a determination of the Hubble constant to a precision of better than 5%; a characterization of the primeval lumpiness; and possible detection of the relic gravity waves from inflation. The precision maps of the CMB that will be made are crucial to establishing Inflation + Cold Dark Matter (see e.g., Bennett et al, 1997).

- Map of the Universe today. Our knowledge of the structure of the Universe is based upon maps constructed from the positions of some 30,000 galaxies in our own backyard. The Sloan Digital Sky Survey (SDSS, 1998) will produce a map of a representative portion of the Universe, based upon the positions of a million galaxies. The Anglo-Australian Two-degree Field survey will determine the position of several hundred thousand galaxies (2dF, 1998). These surveys will define precisely the large-scale structure that exists today, answering questions such as, "What are the largest structures that exist?" Together, the CMB map of the young Universe and the SDSS/2dF map of the Universe today will definitively test the Cold Dark Matter theory of structure formation, and much more.

- Cold dark matter. A key element of theory is the cold dark matter particles that hold the Universe together; until we actually detect cold dark matter particles, it will be difficult to argue that cosmology is solved. Experiments designed to detect the dark matter that holds are own galaxy together are now operating with sufficient sensitivity to detect both neutralinos and axions (Sadoulet, 1999). In addition, experiments at particle accelerators (Fermilab and CERN) will be hunting for the neutralino and its other supersymmetric cousins.

- Nature of the dark energy. If the Universe is indeed accelerating, then most of the critical density exists in the form of dark energy. This component is poorly understood. Equally puzzling is why it is just now come to be the dominant component of the mass/energy budget: its energy density is constant (or slowly varying) and the matter density decreases as the volume of the Universe increase, and thus in the past it was unimportant and in the future matter will be unimportant. Independent evidence for the existence of this dark energy, e.g., by CMB anisotropy, the SDSS and 2dF surveys, or gravitational lensing, is crucial. Additional measurements of SNeIa could help shed light on the precise nature of the dark energy: there are interesting possibilities beyond vacuum energy. The dark energy problem is not only of great importance for cosmology, but for fundamental physics as well. Whether it is vacuum energy or quintessence, it is a puzzle for fundamental physics and likely a clue about the unification of the forces and particles.

- Present expansion rate H_0. Direct measurements of the expansion rate using standard candles, gravitational time delay, SZ imaging and the CMB maps will pin down the elusive Hubble constant once and for all. It is the fundamental parameter that sets the size – in time and space – of the observable Universe. Its value is critical to testing the self consistency of Cold Dark Matter.

- Dark matter bookkeeping. Our best knowledge of the amount of matter in the Universe is based upon clusters of galaxies. Two new X-ray observatories – NASA's AXAF and ESA's XMM – will be launched in 1999, and data they take will strengthen and refine our understanding of dark matter based upon clusters of galaxies. Further, a powerful new tomographic technique for studying clusters when combined with x-ray measurements will sharpen measurements of dark matter in clusters. (The technique, Sunyaev – Zel'dovich or SZ imaging, uses the fact that some fraction of CMB photons that pass through a cluster have their energies changed slightly.) Until a decade ago, almost all knowledge of the distribution of matter in the Universe was based upon the distribution of light. Gravitational lensing by dark matter has begun to reveal the distribution of matter; this technique, which requires CCD cameras with 100s of millions of pixels and telescopes with wide fields of view, will undoubtedly help us to better understand the distribution of dark matter and test the Cold Dark Matter hypothesis (Tyson, 1993).

- Big-bang nucleosynthesis. We should not forgot possible insights that could come from more precisely probing the standard cosmology. The Tytler – Burles deuterium measurement and pegging of the density of ordinary matter makes it possible to very precisely predict the big-bang abundance of ^{4}He, $24.6\% \pm 0.1\%$. Current measurements of the primeval ^{4}He abundance are not nearly so precise, $24\% \pm 1\%$. Further measurements of the ^{4}He abundance have the potential to test this powerful probe of the hot big-bang model and to strengthen the foundations of cosmology (or to shake them!).

6 Looking Forward

Because this is a debate, I have been purposefully provocative (as my colleagues can testify, even more so than usual). The scientist in me appreciates that we are still far from "Cosmology Solved," and that the solution may be richer than or even radically different from Inflation + Cold Dark Matter. Big surprises could still be ahead. Still, I think I can see the top of the mountain emerging through the haze.

By any measure, Cosmology is entering a Golden Age, as prophesied by David Schramm. We have a well established foundation in the hot big-bang model; we have bold and expansive theoretical ideas born of the inner space / outer space connection, and now, we are seeing the beginning of an avalanche of high-quality observations that will test these ideas – 1998 was only the tip of the iceberg!

It may well be – and it is certainly my opinion – that 1998 is remembered as the year that Inflation + Cold Dark Matter became a part of the standard cosmology. Or, it may be written that 1998 was zenith for Inflation + Cold Dark Matter, and it was downhill for it thereafter. If the latter proves to be true, armed with an enormous amount of information about the origin and evolution of the Universe and with expectations for learning even more, we will have to go back to the drawing board for new ideas. And there is no doubt that those ideas will have to come from the inner space / outer space interface.

If Inflation + Cold Dark Matter does pass the series of stringent tests that will confront it in the next decade, there will be questions to address and issues to work out. Exactly how does inflation work and fit into the scheme of the unification of the forces and particles? Does the quantum gravity era of cosmology, which occurs before inflation, leave a detectable imprint on the Universe? What is the topology of the Universe? Are there additional spatial dimensions, and if so, how many and how big? Precisely how did the excess of matter over antimatter develop? What happened before inflation? What does Inflation + Cold Dark Matter teach us about the unification of the forces and particles of Nature? And then there is the amazing zoo of objects in the Universe to understand.

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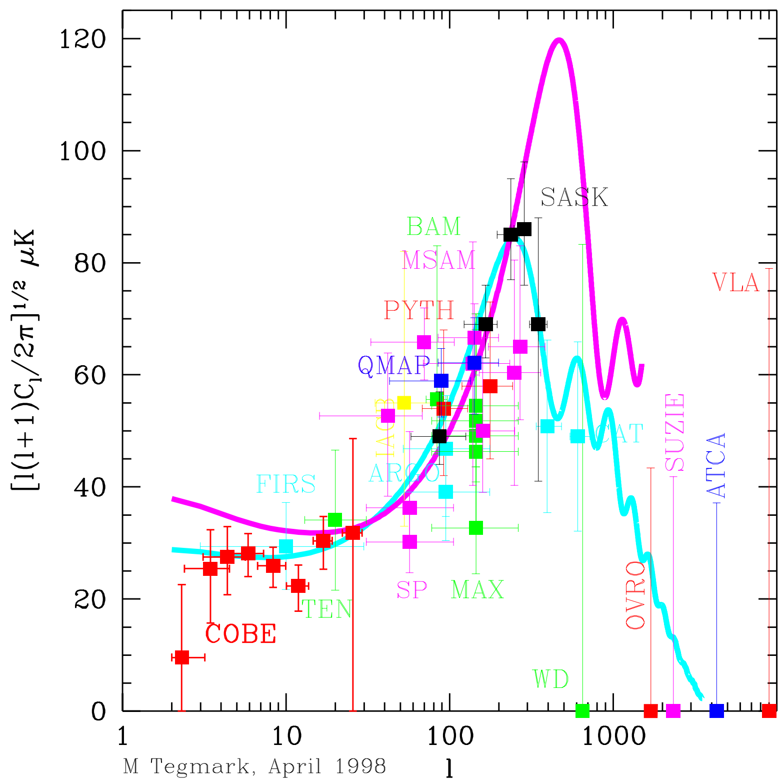

Figure 1: Summary of all CMB anisotropy measurements, where the CMB temperature variation across the sky has been expanded in spherical harmonics, $\delta T(\theta, \phi) = \sum_i a_{lm} Y_{lm}$ and $C_l \equiv \langle |a_{lm}|^2 \rangle$. In simple language, this plot shows the size of the temperature variations between two points on the sky separated by angle θ (ordinate) vs. multipole number $l = 200^\circ/\theta$ ($l = 2$ corresponds to 100°, $l = 200$ corresponds to $\theta = 1^\circ$, and so on). The curves illustrate the predictions of CDM models with $\Omega_0 = 1$ (curve with lower peak) and $\Omega_0 = 0.3$ (darker curve). Note: the preference of the data for a flat Universe, and the evidence for the first of a series of "acoustic peaks." The presence of these acoustic peaks is a key signature of the density perturbations of quantum origin predicted by inflation (Figure courtesy of M. Tegmark).

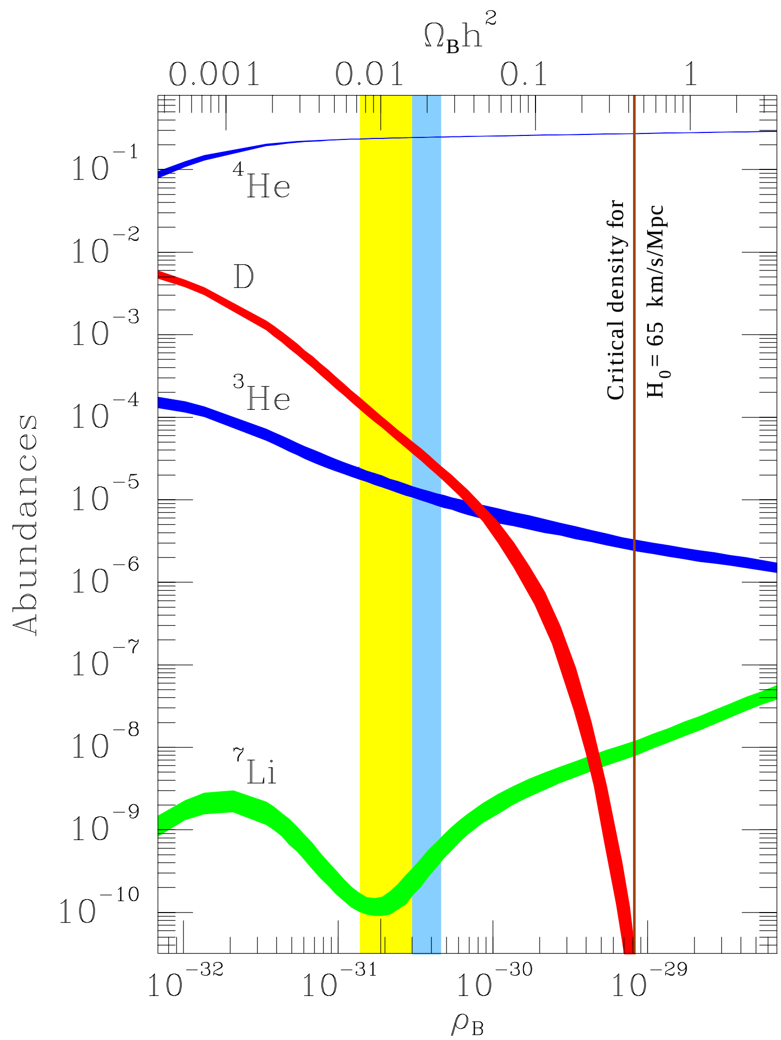

Figure 2: Predicted abundances of ^{4}He, D, ^{3}He, and ^{7}Li (relative to hydrogen) as a function of the density of ordinary matter (baryons). The full band denotes the concordance interval based upon all four light elements that dates back to 1995. The darker portion highlights the determination of the density of ordinary matter based upon the recent measurement of the primordial abundance of deuterium (Burles & Tytler, 1998a,b), which implies that ordinary matter contributes 5% of the critical density.

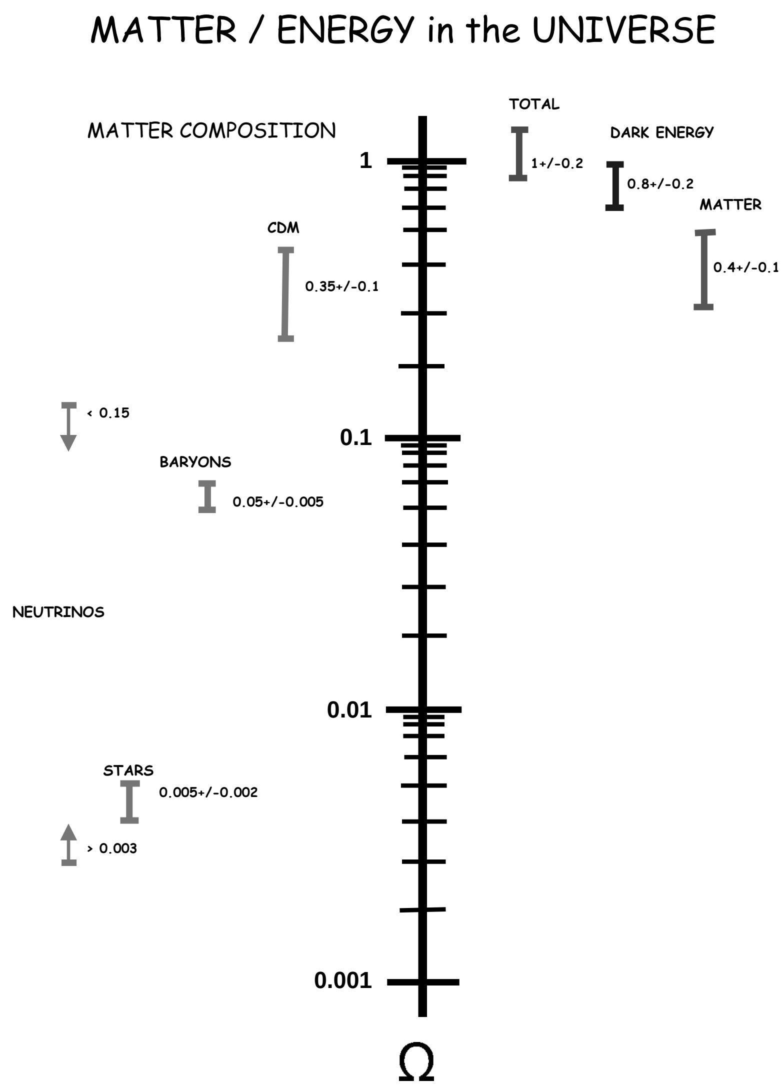

Figure 3: Summary of matter/energy in the Universe. The right side refers to an overall accounting of matter and energy; the left refers to the composition of the matter component. The upper limit to mass density contributed by neutrinos is based upon the failure of the hot dark matter model of structure formation and the lower limit follows from the evidence for neutrino oscillations (Fukuda et al, 1998). Here H_0 is taken to be $65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

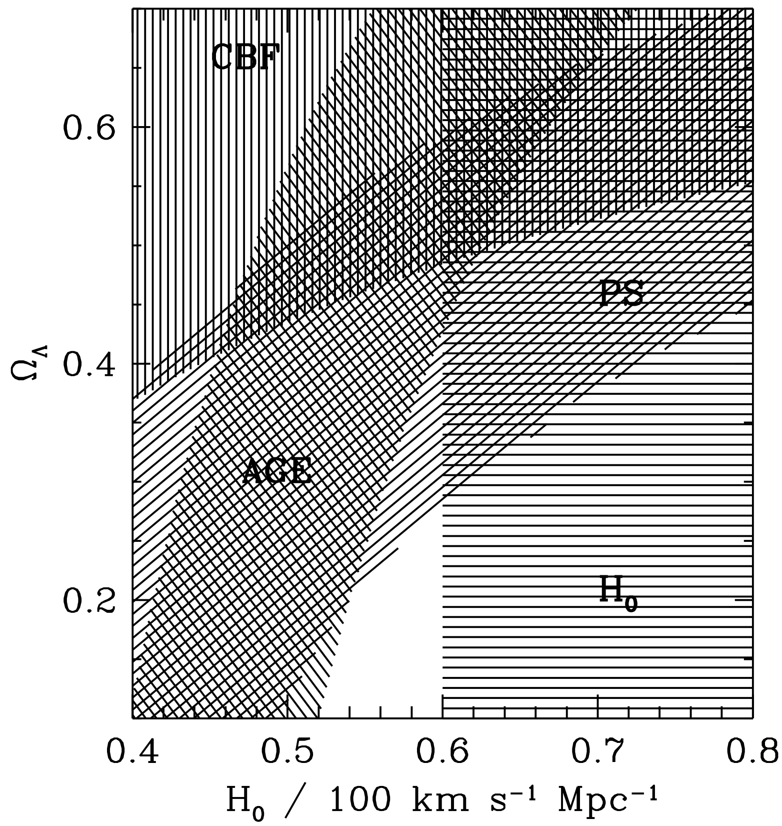

Figure 4: Constraints used to determine the best-fit CDM model: PS = large-scale structure + CBR anisotropy; AGE = age of the Universe; CBF = cluster-baryon fraction; and H_0= Hubble constant measurements. The best-fit model, indicated by the darkest region, has $H_0 \simeq 60 - 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_\Lambda \simeq 0.55 - 0.65$. Evidence for its smoking gun signature – accelerated expansion – was presented in 1998 by Perlmutter et al and Riess et al.

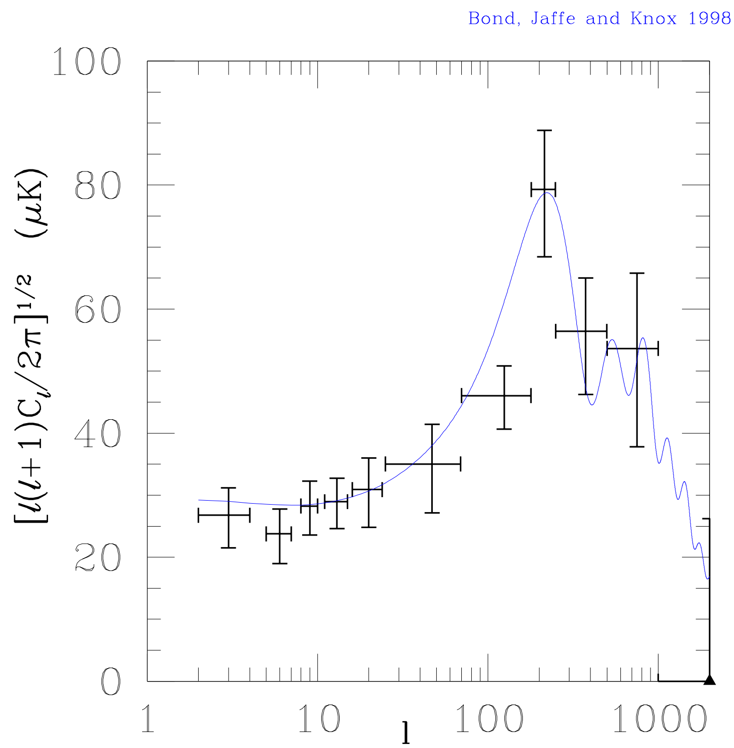

Figure 5: The same data in Fig. 1, but averaged and binned to reduce error bars and visual confusion. The theoretical curve is for the ΛCDM model with $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_M = 0.4$ (Figure courtesy of L. Knox).